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<b>14. ABSTRACT</b> The fundamental activity conducted under this project was to hold a workshop on wave breaking turbulence. The workshop was held October 14-16, 1999, at Cornell University, Ithaca, NY, and organized around laboratory research, field work, numerical modeling, and an integration of these areas. A half day was given to each area, with a format that consisted of a 30-minute talk in the morning, followed by several shorter talks, and then followed by free discussion. Important areas for future research were identified.					
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## International Workshop on Wave Breaking Turbulence, '99

October 14-16, 1999  
Cornell University, Ithaca, New York

*End of Award Report to the Office of Naval Research*  
January 4, 2001

E. A. Cowen, P. L.-F. Liu  
*Cornell University*  
D. T. Cox  
*Texas A&M University*

### Activities

The fundamental activity conducted under this project was to conduct a workshop on wave breaking turbulence. The idea of a workshop focused on wave breaking turbulence was discussed between Philip Liu (Cornell University), Edwin Cowen (Cornell University), and Daniel Cox (Texas A&M University) in January, 1999. Over thirty researchers in the nearshore community were contacted, including representatives from universities and national laboratories in the U.S. and abroad. The response to the proposed workshop was very strong. The workshop was scheduled for October 14 - 16, 1999, at Cornell University, Ithaca, New York. The workshop was organized around laboratory research, field work, numerical modeling, and an integration of these areas. A half day was given to each area, with a format consisted of a thirty minute talk in the morning, followed by several shorter talks, and then followed by free discussion.

The workshop participants gratefully acknowledge the financial support of both the National Science Foundation and the Office of Naval Research. Five distinct programs within the National Science Foundation provided support, three within the Engineering Directorate: Division of Civil & Mechanical Systems, Hazard Reduction Program (Clifford J. Astill, Program Director); Division of Chemical & Transport Systems, Fluid Dynamics and Hydraulics Program (John F. Foss, Program Director); Division of Bioengineering and Environmental Systems, Environmental Technology Program (A. Frederick Thompson, Program Director); and two within the Geosciences Directorate: Division of Ocean Sciences, Physical Oceanography (Eric C. Itsweire, Program Director); Division of Earth Sciences, Hydrologic Sciences (L. Douglas James, Program Director). Significant support was also provided by the Office of Naval Research, Department of Ocean, Atmosphere, and Space Science and Technology, Sensing and Systems Division, Coastal Dynamics Program (Thomas Kinder, Team Leader).

## Workshop Agenda

**International Workshop on Wave Breaking Turbulence '99**  
*Sponsored by the National Science Foundation and Office of Naval Research*  
October 14-15, 1999 (McManus Lounge, 166 Hollister Hall)

### THURSDAY, OCTOBER 14

7:45 - 8:20      BREAKFAST AND REGISTRATION

**Field research session, Moderators Tim Stanton and Ed Thornton**

8:20 - 8:35      Opening Remarks  
8:35 - 9:05      Dr. Tim Stanton and Dr. Edward Thornton, Naval Postgraduate School  
9:05 - 9:20      Dr. Eugene A. Terray , Woods Hole Oceanographic Institution  
9:20 - 9:35      Dr. David M. Farmer, Institute of Ocean Sciences  
9:35 - 9:50      Dr. Eric Terrill and Dr. W. Kendall Melville, Univ. of California at San Diego  
9:50 - 10:05      Dr. Stefan Aarninkhof and Dr. Marcel Stive, Delft University of Technology  
10:05 - 10:15      Dr. Harry Yeh, University of Washington  
10:15 - 10:30      Dr. Britt Raubenheimer, Woods Hole Oceanographic Institution  
10:30 - 10:45      BREAK  
10:45 - 12:15      Discussion of field research, Moderators Tim Stanton and Ed Thornton  
  
12:15 - 1:00      LUNCH - Served in McManus Lounge

**Laboratory research session, Moderators Ken Melville and Fred Raichlen**

1:00 - 1:15      Dr. W. Kendall Melville, University of California at San Diego  
1:15 - 1:25      Dr. James H. Duncan, University of Maryland  
1:25 - 1:35      Dr. Donald O. Rockwell, Lehigh University  
1:35 - 1:45      Dr. Emily Pidgeon, Stanford University/Flow Science Incorporated  
1:45 - 1:55      Dr. Chin Wu, University of Wisconsin  
1:55 - 2:05      Dr. Guillemette Caulliez, IRPHE Laboratory  
2:05 - 2:15      Dr. Andrew T. Jessup, University of Washington  
2:15 - 2:25      Dr. Ira Leifer, University of California, Santa Barbara  
2:25 - 2:35      Dr. Yassin Hassan, Texas A & M University  
2:35 - 2:45      Dr. Frederic Raichlen, California Institute of Technology  
2:45 - 2:55      Dr. Javier Lopez and Dr. Inigo Losada, University of Cantabria  
2:55 - 3:05      Dr. Francis Ting, South Dakota State University  
3:05 - 3:15      Dr. Tsutomu Sakakiyama, Central Research Institute of Electric Power Industry  
3:15 - 3:30      BREAK  
3:30 - 4:45      Discussion of laboratory research, Moderators Ken Melville and Fred Raichlen  
  
4:45 - 5:30      Lab Tour and Reception - Defreese Hydraulics Laboratory  
5:30              Bus back to hotel  
  
6:30 - 9:30      Dinner, Dano's Restaurant (1 block from hotel)

## FRIDAY, OCTOBER 15

7:45 - 8:30 BREAKFAST

### Numerical/Analytical research session, *Moderator Phil Liu*

8:30 - 8:43 Dr. Philip L.-F. Liu, Cornell University  
8:43 - 8:56 Dr. Kelli Hendrikson and Dr. Richard K-P Yue, Massachusetts Institute of Technology  
8:56 - 9:09 Dr. Douglas G. Dommermuth, Science Applications International Corporation  
9:09 - 9:22 Dr. Yasunori Watanabe, Hokkaido University/Cornell University  
9:22 - 9:35 Dr. Stefan Mayer, Per Madsen, and Harry Bingham, Technical University of Denmark  
9:35 - 9:48 Dr. Robert A. Dalrymple, University of Delaware  
9:48 - 10:01 Dr. Maurizio Brocchini, University of Genova  
10:01 - 10:12 Dr. Ib Svendsen, University of Delaware  
10:12 - 10:25 Dr. James T. Jenkins, Cornell University  
10:25 - 10:45 BREAK  
10:45 - 12:15 Discussion numerical/analytical research, Moderator Phil Liu

12:15 - 1:00 LUNCH

### Integral research session, *Moderators Kazuo Nadaoka and Marshall Tulin*

1:00 - 1:30 Dr. Kazuo Nadaoka, Tokyo Institute of Technology  
1:30 - 1:45 Dr. Steve Elgar, Woods Hole Oceanographic Institute  
1:45 - 2:00 Dr. Akio Okayasu, Yokohama National University  
2:00 - 2:15 Dr. Daniel Cox, Texas A & M University  
2:15 - 2:30 Dr. Merrick Haller, University of Michigan  
2:30 - 2:45 Dr. Tetsu Hara, University of Rhode Island  
2:45 - 3:00 Dr. Marshall Tulin, University of California at Santa Barbara  
3:00 - 3:15 BREAK  
3:15 - 4:45 Discussion of integral research, Moderators Kazuo Nadaoka and Marshall Tulin  
4:45 - 5:00 Closing Remarks  
5:00 Bus back to hotel

## Saturday, October 16

9:00 - 12:00 Summary session - all invited to participate, 208 Hollister Hall

### Participants

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## International Workshop on Wave Breaking Turbulence, '99

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### 1 Introduction

The wave breaking process itself unifies small- and mid-scale nearshore research, but it is one of the least understood. A report on the state of nearshore processes research from a workshop held in 1989 in St. Petersburg, Florida, listed the dynamics of wave breaking as one of five priority research areas [Holman et al, 1990]. Nearly ten years later, a second workshop at same venue reported wave breaking and the associated turbulence as one of five priority science issues in nearshore research [Thornton, 2000]. The intent of the workshop held in Ithaca was to focus on wave breaking turbulence.

In addition to nearshore processes such as wave transformation, currents, and sediments suspension and transport, wave breaking also plays an important role in gas exchange, dispersion of pollutants, optical and acoustical ocean properties, remote sensing, and the bow waves of ships. A number of researchers in these areas which are traditionally focused on steepness-limited wave breaking were invited to broaden the scope from simply depth-limited wave breaking phenomena.

Our understanding of wave breaking has been limited by several factors, including our inability to make high resolution field measurements due to the harsh environment and high bubble content, the limitations of single point turbulence measurements in the laboratory, the challenge of separating turbulence from unsteady quasi-periodic flows, and the limitations of numerically modeling turbulence in unsteady, multi-phase flow. Recent advances in measurement technology such as acoustic- and laser-Doppler velocimetry in the field and particle image velocimetry in the laboratory as well as numerical modeling techniques such as large eddy simulation have lead to some promising results and we are now at point where these developing technologies are mature enough that they may lead to significant breakthroughs in our fundamental understanding of wave breaking turbulence. Furthermore, research on multi-phase flow in other disciplines such as chemical and nuclear engineering is significantly advanced and these advances could be applied to research on nearshore and ocean processes.

The workshop brought together researchers working on the topic of wave breaking turbulence from these main areas (field, laboratory, numerical) as well as deep water (steepness-limited) and shallow water (depth-limited) wave breaking in an effort to assess the current state of and seek across field guidance for the future of the field of wave breaking turbulence.



## 2 Findings

The following list, generated by reviewing and compiling the abstracts sent by each participant prior to the workshop, notes taken during the workshop, video taken during the workshop, and a summary discussion following the workshop, are the important research areas as identified by the workshop participants.

### Important Research Areas

- Breaking Criteria and Initiation of Wave Breaking
- Turbulence Production and Initial Air Entrainment
- Buoyancy effects and Two-phase (air-water) flow
- Large Eddies and Coherent Motions
- Temporal and Spatial Gradients of Turbulence Intensity and Vorticity
- Effects of Wave Breaking Induced Turbulence on Bottom Boundary Layer Dynamics
- Wave-Turbulence Decomposition and Analysis
- Reconciliation of Direct Turbulence Measurements with Indirect (Integral) Approaches
- Swash Zone Turbulence - Relative Importance of Bore Turbulence and Bed Shear Stress
- Development of Transport Equations for Multi-phase Systems
- Instrumentation
- Numerical Modeling

In view of this list, it is noted that the intent of the workshop was to focus on wave breaking turbulence itself. For this reason, associated research areas such as gas exchange, pollutant mixing, and sediment suspension are not included directly, but the importance of these processes in relation to wave breaking is implicit to many of the listed research areas.

## 3 References

- Holman, R.A., Bowen, A.J., Dalrymple, R.A., Dean, R.G., Elgar, S., Flick, R., Freilich, M., Guza, R.T., Hanes, D., Kirby, J., Madsen, O., Sternberg, R. and Svendsen, I.A (1990) "Report on the state of nearshore processes research." Report from the Nearshore Processes Workshop, St. Petersburg, FL, April 1989, *Rpt. OSU-CO-90-6*, Oregon State University, Corvallis, Oregon.
- Thornton, E., Dalrymple, R.A., Drake, T., Gallagher, E., Guza, R.T., Hay, A., Holman, R., Kaihatu, J., Lippman, T., and Ozkan-Haller, T. (2000) "Nearshore research: Report based on the nearshore workshop, St. Petersburg, FL, September, 1998," <http://www.oc.nps.navy.mil/~thornton/report5.html>.